Key Issues in Hadronic Physics

Abstract

A group of fifty physicists met in Duck, NC, Nov. 6-9 to discuss the current status and future goals of hadronic physics. The main purpose of the meeting was to define the field by identifying its key issues, challenges, and opportunities. The conclusions, incorporating considerable input from the community at large, are presented in this white paper. [1]

[1]This document is to be presented at the Town Meeting at Jefferson Lab Dec. 1-4 and made available to NSAC to aid in the long range planning process. It does not represent a response to the NSAC charge, a historical review of hadronic physics, or an endorsement of any particular experimental effort. RHIC physics is being reviewed in a separate process and is therefore not discussed herein.

Contents

1 Introduction

Strong interaction physics poses a wealth of fundamental questions with profound significance for our understanding of Nature and the structure of the matter of which we and our universe are composed. Answering these questions lies at the heart of contemporary nuclear science and will have deep impact on particle physics, astrophysics, and cosmology.

The field of hadronic physics is the study of strongly interacting matter in all its manifestations and the understanding of its properties and interactions in terms of the underlying fundamental theory, Quantum Chromodynamics (QCD). It is a vibrant and growing field, which now encompasses a large fraction of nuclear physics and has attracted a significant number of particle physicists. The field has a long history, starting with phenomenological descriptions of hadron-hadron interactions and the hadron spectrum and continuing to present day ideas on the quark-gluon structure of hadrons, heavy quark symmetry, effective field theory, the quark-gluon plasma, and novel color superconducting phases of matter among a host of others. Although many of its deepest questions have challenged us for decades, we now have within our grasp unprecedented opportunities for fundamental progress. Recent advances in computational technology, lattice field theory algorithms, continuum model building, accelerator beam quality, and detector design have led us to the threshold of developing a true understanding of the fundamental mechanisms of QCD and the ability to solve nonperturbative QCD quantitatively. This report describes the present status of hadronic physics, the scientific opportunities it provides, and the means by which the national hadronic physics community is poised to exploit these opportunities.

The primary goals of hadronic physics are to determine the relevant degrees of freedom that govern hadronic phenomena at all scales, to establish the connection of these degrees of freedom to the parameters and fundamental fields of QCD, and to use our understanding of QCD to quantitatively describe a wide array of hadronic phenomena, ranging from terrestrial nuclear physics to the behavior of matter in the early universe.

The theoretical foundations and extensive experimental tests of the standard model in general and QCD in particular are so compelling that the focus is not on *testing* QCD but rather on *understanding* QCD. Specific objectives of the field, which are addressed in more detail in the main text of the report, include the following:

- **Determine the parameters of QCD.**

  The fundamental scale, Λ_{QCD}, which sets the scale for all strong interaction phenomena, the masses of quarks which ultimately control details of hadron spectroscopy, and the QCD vacuum Θ parameter controlling the violation of CP symmetry need to be determined precisely.

- **Understand the origin and dynamics of confinement.**

  The remarkable fact that the fundamental constituents of composite hadrons, quark and gluons, cannot be removed from hadrons and examined in isolation sets hadrons apart from all other known composite systems. Whereas lattice calculations clearly indicate the formation of tubes of gluonic fields connecting colored charges, we need to understand from first principles why flux tubes are formed, how they relate to the

confinement of color charge, and the role that they play in the structure and dynamics of hadrons. Experimental exploration of the full spectrum of states composed of quarks and gluons will be an important tool in attaining this understanding.

- **Understand the origin and dynamics of chiral symmetry breaking.**

  The spontaneous breaking of chiral symmetry, responsible for the existence of light pions, their dynamics, and the masses of hadrons needs to be understood directly in terms of QCD. We need to understand the physical origin, topological or otherwise, of the quark zero modes generating the chiral condensate, and to understand the relationship between the deconfinement and chiral phase transitions at finite temperature.

- **Understand the quark and gluon structure of hadrons based on QCD.**

  One of the principal Science objectives in the Department of Energy Strategic Plan is to develop a quantitative understanding of how quarks and gluons provide the binding and spin of the nucleon based on QCD. This objective is a central focus of our field.

- **Understand the relation between parton degrees of freedom in the infinite momentum frame and the structure of hadrons in the rest frame.**

  Deeply inelastic scattering experiments, a major quantitative tool for exploring the quark and gluon structure of hadrons, measure correlation functions along the light cone and thus naturally determine probability distributions of partons in the infinite momentum frame. We need to develop physical insight and quantitative tools to relate parton distributions to the structure of hadrons in their rest frame.

- **Develop quantitatively reliable models and approximations to QCD.**

  The understanding and synthesis of a wealth of existing and forthcoming experimental data requires the development of reliable models. This process will be aided by qualitative insights and constraints arising from the development of controlled expansions of QCD such as the heavy-quark, large-N_c, and chiral limits; from the techniques of effective field theory; and from quantitative and qualitative lattice results.

- **Explore the role of quarks and gluons in nuclei and matter under extreme conditions.**

  From the modification of the quark-gluon structure of a nucleon when it is immersed in the nuclear medium within a nucleus to the novel phases and behavior of matter in neutron stars, supernovae, or the early universe, there are a host of fundamental questions that hinge crucially on developing the ability to understand and quantitatively solve QCD.

The body of this report is organized as follows. We begin by discussing in more detail the fundamental problems arising in strong interaction physics. The next two sections describe two ways to gather experimental information on hadronic physics: using deeply inelastic scattering to study partons in hadrons, and studying quarks and gluons in the excited state spectrum of mesons and baryons. The role of models is discussed in section 5. Finally, new theoretical and experimental tools that promise unprecedented opportunities for fundamental progress in hadronic physics are highlighted in section 6.

2 Fundamental Problems in Strong Interaction Physics

To place the subsequent details of experimental and theoretical exploration of hadronic physics in context, it is useful to begin by considering the truly fundamental problems arising in contemporary hadronic physics.

2.1 Parameters of QCD

There is compelling evidence that in additional to its beauty and theoretical appeal, the QCD Lagrangian completely describes the strong interactions. Hence the challenge is to determine its parameters, solve it, and understand it.

The fundamental scale, Λ_{QCD}, or equivalently the running coupling constant α_S, emerges from QCD through the phenomenon of dimensional transmutation so it is crucial to determine it accurately. At present, the numerical solution of lattice QCD provides one of the most precise values of Λ_{QCD}, which is also in good agreement with state-of-the art experimental determinations. With requisite effort, this evaluation can be improved by an order of magnitude, thereby providing an essential parameter needed to understand the unification of the fundamental forces.

Experiments on the electric dipole moment of the neutron indicate that the value of the θ angle, another fundamental parameter of QCD, is very small. This leads to a major puzzle called the strong CP problem. Since one possible resolution would be for the up quark mass, m_u, to be zero, it is particularly important to measure the renormalization group invariant mass ratio, $\frac{m_d - m_u}{m_d + m_u}$. A combination of theoretical analysis based on chiral perturbation theory and numerical lattice calculations make it possible to calculate this ratio convincingly within the next five years, and this is a high priority, showcase calculation. It is also of interest and feasible to determine the absolute masses of the strange quark, $\mathrm{m}_s(\mathrm{m}_Z)$ and of the heavy quarks.

2.2 How does QCD work?

Although a quarter of a century has passed since the experimental discovery of quarks in the nucleon and the invention of QCD, understanding how QCD works remains one of the great puzzles in many-body physics. One major challenge arises from the fact that the degrees of freedom observed in low energy phenomenology are totally different from those appearing in the QCD Lagrangian. Indeed, unlike any other many-body system, the individual quark and gluon constituents making up a proton cannot even be removed from the system and examined in isolation. In addition, in the past, there were no quantitative tools to calculate non-perturbative QCD. Now, however, the combination of theoretical tools and experimental probes presently available offers an unprecedented opportunity to make decisive progress in understanding how QCD works.

2.2.1 Fundamental Aspects

There are three fundamental questions upon which all else hinges. What are the degrees of freedom and mechanisms responsible for confinement, for chiral symmetry breaking, and for

U(1) symmetry breaking? Understanding these mechanisms from first principles and developing the tools to calculate them quantitatively will provide the foundation for understanding hadronic physics.

Several analytical approaches provide valuable insight and theoretical guidance. Semi-classical objects including instantons, monopoles, and vortices identify essential nonperturbative effects that may play significant roles in confinement, chiral symmetry breaking, and η' mass generation. The strong coupling expansion and the related emergence of flux tubes provides strong insight into the physics of confinement. Expansions around three complementary analytically tractable limits provide valuable insight into the physical regime. The heavy quark limit emphasizes the universal adiabatic behavior of glue and light quarks in the presence of static color sources. The chiral limit emphasizes the role of pion degrees of freedom in the kinematical regime in which excitations of heavier degrees of freedom are suppressed. Studies based on this limit can describe the long range part of hadronic structure and interactions in a controlled way. Finally, the large N_c limit emphasizes the simplifications in the classes of diagrams that contribute, and the mean field effects that arise, when the number of colors is large.

The advances in lattice field theory and the availability of very large scale computers make it possible for the first time to complement these analytic approaches with definitive numerical solutions of QCD for a large class of important problems. In addition to enabling quantitative calculation of physical quantities like the chiral condensate, topological susceptibility, string tension, and interface energy between confined and deconfined phases, the lattice provides important opportunities for insight. For example, one can directly explore the dependence of these quantities on the number of flavors, the number of colors, and the values of quark masses and thereby test theoretical mechanisms in ways that are impossible with laboratory experiments. In addition, one can directly determine the configurations which dominate the QCD path integral and attempt to extract qualitative features of them. Finally, one can use lattice calculations to constrain and improve models, for example by evaluating overlaps between exact wavefunctions and model *Ansätze*.

2.2.2 Hadron Structure – Two Complementary Perspectives

It is natural to view the structure of hadrons from two very different and complementary perspectives. The challenge is not only to complete our understanding from each viewpoint, but also to relate the degrees of freedom arising in one description to those appropriate to the other.

Snapshots in quarks and glue

Asymptotic freedom enables us to use the tools of perturbative QCD to precisely characterize deeply inelastic lepton scattering from hadrons. Since these experiments measure correlations along the light cone, the resulting structure functions are naturally described by the light cone distributions of quarks and gluons, or equivalently, quark and gluon distributions in the infinite momentum frame. These experiments first revealed quarks and gluons in the nucleon and have now determined the light cone quark distribution, helicity distribution, and gluon distribution in great detail. An important conceptual advantage of these distributions is that the quarks and gluons they measure are directly related to the quark and gluon degrees of freedom appearing in the QCD Lagrangian. One limitation is

that they tell us the probability of finding a quark with a given momentum fraction, x, but yield no information about the phase of the amplitude.

Whereas perturbative QCD is crucial in extracting these distributions from experiments, it is totally inadequate for the deeper challenge of calculating them from first principles. Thus, it is a major development that contemporary theory has become sufficiently powerful to calculate low moments of these distributions nonperturbatively.

Experiments now have the potential to tell us in detail how the total spin of the proton is divided between the spin and orbital angular momentum of quarks and gluons. Measurements of higher twist effects can specify, for example, correlations between quarks and gluons. A particularly interesting and novel possibility arises from the fact that the gluon component of the nucleon grows as the momentum fraction x decreases, so that very low x physics provides a new regime dominated by a sea of gluons. Thus, experimental study of very low x offers the tantalizing possibility of exploring this new gluon dominated regime in which essential simplifications in QCD may occur and a new form of universal behavior may arise.

Pictures with dressed quarks

The other natural perspective from which to view hadron structure is in the rest frame; which is appropriate for consideration of spectroscopy and measurements of quantities like the charge radius, magnetic moment, and axial charge. This is the frame in which the familiar quark model works far better than we can presently justify from first principles. Here, the degrees of freedom are not simply those of the Lagrangian and we need to understand their microscopic foundations. What is the relevant quark degree of freedom, the so-called constituent or dressed quark, and how is it related through its cloud of gluons and quark-antiquark pairs to the quark and gluon fields of the underlying Lagrangian? How do the resulting quasiparticles interact? Although we know that essentially all of the mass and half the momentum and spin of the nucleon are carried by glue, what is the role of this glue in the nucleon, and how can we observe it? Is it concentrated in flux tubes associated with confinement, and if so, can we find unambiguous signatures in spectroscopy such as states with exotic quantum numbers arising from excitation of flux tubes? To what extent are lumps of glue associated with instantons responsible for the nonperturbative interactions between quarks in light hadrons? How does the dressed quark picture manifest the underlying chiral symmetry structure of QCD and thereby produce the known long distance behavior of hadrons described by chiral perturbation theory? Well chosen spectroscopy, in concert with theoretical analyses of hadron wave functions and vacuum structure, offers the potential for crisp answers to many of these difficult conceptual questions that have puzzled us for decades.

2.2.3 Nuclear Physics

The next intellectual challenge is to go beyond the physics of a single hadron and understand essential aspects of nuclear physics from first principles. In thinking about many-nucleon systems, one immediately faces the question of the origin of the nuclear energy scale. Why, when the natural energy scale of QCD is of the order of hundreds of MeV, is the nuclear binding energy per particle so small, of the order of 10 MeV? Does it arise from complicated details of near cancellations of strongly attractive and repulsive terms in the nuclear

interaction or is there some deeper reason for this scale to arise?

Calculations in small A nuclei from QCD

The large separation between the hadronic energy scale and the nuclear binding scale renders it difficult to apply QCD directly to understand the physics of small A nuclei. However, quantitative calculations based on effective field theory techniques that arise from chiral symmetry provide an alternative approach. Traditionally, this method has been applied to the physics of pions in the context of chiral perturbation theory. Currently, it is being extended to address many nucleon interactions. When combined with first principles calculations of the low energy constants from QCD, these effective field theories may have the potential to provide a systematic and quantitative tool to study low energy properties of light nuclei. If quantitative models of low energy QCD are developed, it would be valuable to use them to derive the gross features of low-A nuclear physics and thereby illuminate how the macroscopic features of nuclear physics emerge from the underlying quark and gluon degrees of freedom.

Insight into large A from QCD

It is harder to envision understanding the physics of large A nuclei, nuclear matter, and neutron star matter from effective field theory alone. Given the success of nuclear many-body theory based on phenomenological potential fits to nucleon-nucleon phase shifts, it would be valuable to understand qualitative features of these potentials directly from QCD – for example the origin of the hard core and the spin and isospin dependence of the nucleon-nucleon interaction. The heavy quark limit is particularly valuable in this regard, since one can calculate the adiabatic potential between hadrons containing one heavy quark on the lattice and thereby explore the role of light quark exchange and gluon exchange in detail. The large N_c limit is also useful in elucidating certain features of hadron-hadron interactions.

In addition to understanding the structure of nuclei *per se*, it is also of interest to understand the behavior of nucleons within nuclei. Over a decade ago, deeply inelastic scattering experiments by the EMC collaboration and its successors showed that the quark distribution in a nucleon immersed in the nuclear medium differs substantially from that in free space. Whereas the calculational tools at that time were inadequate to discriminate between several plausible mechanisms, we now have the opportunity to clarify this physics.

2.3 QCD in the wider world

QCD is the essential ingredient of the Standard Model that is not yet under quantitative control. Precise calculations based on it are necessary to understand a variety of phenomena in high energy physics and astrophysics that extend far beyond the traditional boundaries of nuclear physics. Furthermore, there are illuminating connections between QCD and condensed matter physics from which both fields can benefit.

2.3.1 High Energy Physics and Astrophysics

The design and interpretation of experiments to search for fundamental physics beyond the standard model rely on firm quantitative control of QCD. At present, the largest uncertainty in many high energy physics calculations comes from incalculable strong interaction matrix elements. For example, the matrix element $\langle P|m_s\bar{s}s|P\rangle$ is necessary to determine whether the

neutralino, a supersymmetric particle, can help solve the "dark matter" puzzle. Calculation of this strangeness matrix element in the proton state is necessary to quantify the coupling of the neutralino to matter.

Other calculations are necessary to understand the relation between the fundamental quark and gluon interaction parameters with the mixing of K and $\bar{K}$ mesons or with the electric dipole moment of the neutron. These calculations can shed light on how one of the fundamental symmetries of nature, a combination of charge conjugation and parity, is violated.

The mass difference between the proton and the neutron, $m_N - m_P$, is an energy scale that is crucial to the structure of our world. A grand challenge that would truly test our mastery of QCD would be to calculate it from first principles. This involves an interesting interplay of electromagnetic interactions and the difference between the up and down quark masses.

2.3.2 Extreme Conditions in the Lab and the Cosmos

QCD is essential to answer questions related to the physics of the early universe and high energy astrophysics. For example, just after the big bang, when matter was extremely hot, QCD predicts that quark and gluon degrees of freedom dominated the world. As the universe cooled, these degrees of freedom were bound into hadrons, reducing the number of degrees of freedom dramatically. The temperature and the nature of this qualitative change in the phase of matter is an extremely interesting question for cosmologists. The search for the new state of matter at high temperatures and densities is currently being undertaken in relativistic heavy ion experiments.

Observation of ultra high energy cosmic rays with energies of the order of 10^{11} GeV implies that neutrinos with similar energies must also be present. If the large arrays of neutrino detectors that are planned in the future can detect this flux of neutrinos, they can act as laboratories for a new form of deeply inelastic scattering experiments. Learning about the structure functions of the proton at low x will be crucial to interpret the results of these experiments.

The physics of QCD at high densities plays a critical role in determining the physics of neutron stars and supernovae. The equation of state at finite density is essential for quantitative calculations of the astrophysics of neutron stars. The excitation spectrum of hadronic matter must be understood to predict their neutrino emission spectra. Recently the theoretical exploration of novel phenomena in quark matter at high density, such as color superconductivity and color-flavor locking, has given new impetus to understanding QCD at high density and its astrophysical consequences. As our quantitative understanding of this regime develops, it may also provide new insight into the domain of ordinary nuclear densities. Indeed, one of the fundamental questions we must ultimately address is the nature of the true ground state of hadronic matter. Is it really true, as is usually assumed, that the ground state of hadronic matter resembles a collection of conventional nuclei, or is such a state a metastable excitation of the true ground state comprised of up, down, and strange quarks? The definitive calculation of the ground state of matter is another worthy Grand Challenge for hadronic physics.

2.3.3 Connections with Condensed Matter Physics

The phenomena and challenges that arise in hadronic physics have much in common with those arising in strongly interacting condensed matter systems. For example, the complex dynamics of QCD simplifies at certain critical points in the QCD phase diagram leading to universal critical behavior, which can be modeled with much simpler degrees of freedom such as those arising in the Ising model. Similarly, the superfluid phases of ^{3}He have much in common with phases in dense QCD. Lattice QCD can be formulated in the language of quantum spin systems, to which cluster algorithms and the insights from dimensional reduction directly apply. Finally, the notorious fermion sign problem that pervades Monte Carlo calculations in condensed matter problems also arises in QCD, and the invention of techniques to solve it in QCD offers corresponding benefit in condensed matter physics. Thus, the deep interconnections between the physics of strongly interacting systems with many degrees of freedom in condensed matter physics and hadronic physics offers the potential for mutually beneficial sharing of insights and techniques.

3 The Quark and Gluon Structure of Hadronic Matter as Probed through Hard Scattering and Form Factors

Nucleons are the primary building blocks of atomic nuclei and other hadronic matter in the universe. The first direct evidence that the nucleon is a composite particle came from the experimental measurement of elastic form factors in the 1950's. The quark substructure of the nucleon was clearly revealed through electron-proton deeply inelastic scattering (DIS) at SLAC. Following these pioneering discoveries, a great amount of information about the partonic (quark and gluon) structure of hadronic matter has been learned through measurements of form factors and quark and gluon distributions. However, our knowledge is still far from complete. Some crucial questions in this field remain open:

1. *What is the* structure *of hadrons in terms of their quark and gluon constituents?*
2. *How do quarks and gluons evolve into hadrons via the dynamics of confinement?*
3. *What is the role of quarks and gluons in the structure of atomic* nuclei*? How can nuclei be used to study matter under* extreme conditions*?*

The answer to these questions is the missing key to our ultimate understanding of the microscopic structure of matter. In the following subsections, we examine the physical content of these questions and explore future opportunities in this field.

3.1 Hadronic Structure

Understanding the structure of the nucleon in terms of the quark and gluon constituents of QCD is one of the outstanding fundamental problems in physics. The field-theoretical nature of strong interactions leads to the picture of a nucleon as an ensemble of a large and

ever-changing number of constituents. A major aim of experiments through the next decade is to take detailed "snapshots" of this structure at various levels of resolution. The highest resolution is provided by highly energetic projectiles, which interact with individual quarks, antiquarks, and gluons inside a proton or neutron. These interactions, being sensitive to the motion of the struck particle, can map the probability for finding the various constituents as a function of x – the fraction they carry of the nucleon's overall momentum. Such detailed maps will provide a crucial test of QCD-based calculations of nucleon structure. Indeed, a number of basic features have yet to be delineated or understood. At the same time, less energetic projectiles must be used to obtain a lower resolution, but more global, view of the nucleon's properties, *e.g.* elastic form factors, which describe the overall distribution of charge, magnetism, and the magnetic dipole moment of baryonic resonances.

From a large body of available experimental data, the up and down quark distributions at moderate x are found to be consistent with the simple picture of quark models. Gluons also play a crucial role since they carry nearly 50% of the nucleon's momentum. Over the past 5 years, precision measurements from polarized DIS indicate that the quark spins account for only about 30% of the nucleon's spin, in marked contrast with the constituent quark picture, where the quark spins carry all of the nucleon's spin. The credibility of the data is backed by the verification of the so-called Bjorken sum rule – a relation which follows directly from QCD. In addition, contrary to naive expectations, data from Drell-Yan and electroproduction experiments show a pronounced excess of $\overline{d}$ over $\overline{u}$ quarks at intermediate values of x, possibly indicating the importance of Goldstone boson degrees of freedom in nucleon structure.

Unfortunately we do not have a detailed or comprehensive knowledge of nucleon structure. Exciting and fundamental discoveries have yet to be made in multiple frontiers, as illustrated by the following examples.

3.1.1 Strangeness in Nucleons

Strange quarks in the nucleon arise from "vacuum fluctuations". However, the pattern of strange quark effects shows interesting irregularity. Some observables have little or no influence from strange quarks, while strangeness makes a significant contribution to others. From the study of pion-nucleon scattering, it was found that strange quarks are responsible for a sizable fraction of the nucleon mass. Furthermore, polarized DIS data with the assumption of SU(3) quark flavor symmetry hint that s quarks may carry as much as -10% of the nucleon spin. On the other hand, data from DIS with neutrino beams and other experiments indicate that s quarks account for only a few percent of the nucleon's total momentum and that the s and $\overline{s}$ distributions seem similar. Some of the important theoretical and experimental questions to be answered include: Are s and $\overline{s}$ distributions really similar? If so, why? How do strange quarks contribute to the nucleon's magnetic and electric form factors? How can we understand the pattern of the strange quark effects? Experiments, which are actively under way, address some of these questions, such as the strange form factors.

3.1.2 Spin of the Nucleon

How does the proton get its spin? Polarized DIS data have shown that quark spins account for only about 30% of the proton spin. Where are the missing contributions? Besides the quark orbital angular momentum, gluons are expected to be strongly polarized. Indeed a precision QCD analysis of polarized DIS data and recent measurements of hadron-pair production have given a preliminary indication of a large gluon polarization ΔG. In the near future, determining ΔG with good precision is one of the most important objectives in high-energy spin physics. While proton-proton collision experiments are expected to play a crucial role in understanding the behavior of polarized gluons, high-energy polarized electron-proton collisions can provide interesting complementary information.

One possible source of the strong deviation of the measured quark spin contribution from that expected by assuming that it is all carried by valence quarks is a significant polarization of sea quarks. A direct measurement of this will provide an immediate test of various, more sophisticated, nucleon models, which give qualitatively different predictions for the polarization of the antiquarks. Experiments in progress and planned will directly study this question.

3.1.3 Structure Functions at Large x

Our knowledge of the quark distributions at large x is sketchy at best. The regime $x \to 1$ represents a fascinating kinematic limit, where a single parton is responsible for the entire momentum of the proton. The main problem with existing data on the ratio $u(x)/d(x)$ is that the experiments rely on the use of the deuteron to provide a neutron target. The Fermi motion and binding of the neutron in this nuclear bound state introduce large uncertainties in the partonic interpretation of the data in the limit $x \to 1$. New experiments that eliminate this problem are a high priority. In the same limit, it is expected that the struck parton carries the entire spin of the proton as well as its momentum, and so the double spin asymmetry A_1 should approach unity. This expectation must be tested soon. The importance of parton distributions at large x is also reflected in their use as essential input to high energy experimental searches for physics beyond the Standard Model.

A promising new tool for studying large-x behavior is found in the use of quark-hadron duality, first discovered by Bloom and Gilman. Recent precise measurements suggest that the nucleon resonance region can be used to determine reliably the large x behavior of structure functions, which would be difficult to measure using the canonical kinematics of DIS. Duality in semi-inclusive processes remains to be explored.

3.1.4 New Parton Distributions

Besides the unpolarized $q(x)$ and helicity-dependent $\Delta q(x)$ quark distributions, a complete description of nucleon structure at leading order requires the *transversity* distribution $\delta q(x)$. This distribution describes quark polarization within a transversely polarized nucleon and does not mix with gluons under scale evolution. In the absence of relativistic effects, the transversity distribution $\delta q(x)$ should be equal to $\Delta q(x)$, and this provides a "baseline" for our understanding of this, as yet unmeasured, distribution. The first moment of $\delta q(x)$ (termed the tensor charge of the nucleon) offers a promising point for comparison with theory.

Because $\delta q(x)$ decouples from inclusive DIS, semi-inclusive experiments with transversely polarized targets are needed for dedicated measurements of this unknown quantity.

A significant development in hadronic physics over the last several years is the identification of a new class of parton distributions, known as *Generalized Parton Distributions* (GPD). Probed primarily in exclusive measurements, the GPDs describe hard scattering processes that involve the *correlations* between partons. This new formalism offers an exciting bridge between elastic and deeply inelastic scattering: in different kinematic limits of the GPDs, one recovers the familiar elastic form factors and DIS structure functions of the proton. Clearly, a mature description of the partonic substructure of the nucleon, beyond the naive picture of collinear non-interacting quarks, must involve a description of these partonic correlations. Further, GPDs have a direct connection to the unknown parton orbital angular momentum (which is an essential contribution to the total spin of the nucleon) and to the impact parameter dependence of parton distributions. Experimentally, exclusive scattering measurements at large Q^2 and small t, the so-called deep-exclusive scattering (DES), are just beginning. It is essential to continue vigorous theoretical and experimental studies of these interesting new parton distributions.

High t exclusive reactions are the most direct way of observing partonic correlations. The ability to carry out such experiments has been demonstrated in JLab experiments on elastic form factors, $N \to N^*$ amplitudes, wide angle Compton scattering, and ϕ photoproduction. At a specific value of t, these different reactions probe different characteristics of the GPDs. Thus, these quantities put very precise constraints of any models of generalized parton distributions. Since t is directly related to the mean transverse momentum of the participating partons, the t dependence of these reactions yields a measure of the transverse high momentum components of the parton distributions and correlations.

3.1.5 The Partonic Substructure of Mesons and Hyperons, SU(3) Flavor Symmetry

Whereas the proton and neutron are the "building blocks" of atomic nuclei, pions and kaons (and mesons in general) supply the "mortar" that holds the nucleus together. At a fundamental level, pions and kaons are the Goldstone bosons of spontaneously broken chiral symmetry. A familiar example of Goldstone bosons comes from the existence of phonons in crystalline materials due to spontaneously broken translational symmetry.

We know little about the partonic substructure of mesons. Since these particles are unstable on time scales of order 10^{-8} sec or less, they cannot be used as viable fixed targets. However, some measurements have been made using either meson beams or by scattering from the virtual meson cloud around the nucleon. These first data are exciting, but of low precision. A new experimental program is required if one wants to answer these questions: Is the structure of mesons similar to that of baryons? Do sea quarks and gluons play as prominent a role in the substructure of the chiral Goldstone boson as they do in the proton? And most fundamentally, how is the transition from partonic degrees of freedom to Goldstone modes accomplished?

If one were to map out the substructure of the pion and kaon, important tests of so-called SU(3) flavor symmetry might be performed. One of the basic precepts of the strong interaction is that it is "flavor blind": only the quark mass term of the QCD Lagrangian

distinguishes one quark flavor from another. Since the light quark masses are small compared with the physical scale of strong interactions, the structure of the meson should have an approximate flavor symmetry. Independent measurements of the substructure of several of the pseudo-scalar mesons would provide a powerful test of this fundamental precept.

Furthermore, experimental techniques exist that enable the measurement of the partonic substructure of *hyperons*. These are $J^P = \frac{1}{2}^+$ baryons like the proton that contain a strange quark in the valence sector. Hyperons are also being studied with models and lattice QCD. These investigations will permit the detailed exploration of SU(3) symmetry in the baryon sector, where extensive information on the two lightest members is already available. Lastly, DES is capable of comparing parton densities in different baryons: nucleons, Δ-isobars, and hyperons and to probe short distance $q\bar{q}$ wavefunctions of different mesons.

3.2 Hadronization: The Dynamics of Physical State Formation

A fundamental question in hadronic physics is how a quark or gluon from high-energy scattering evolves into a hadron. This process is known as *hadronization*, and is a clear manifestation of color confinement: the asymptotic physical states detected in experiment must be color-neutral hadrons. Hadronization also appears in an astrophysical context, as part of the transition from a deconfined state of free quarks and gluons in the Big Bang into stable protons, which provide the seeds for nuclear synthesis. Understanding fragmentation in spin-dependent processes, the use of fragmentation as a tool for hadron structure study, and probing the global structure of the hadronic final state are likely to be the main themes of future investigation in this area.

3.2.1 Testing the Dynamics of Confinement

Hadronization is a complex, non-perturbative process that is related to both the structure of hadronic matter and to the long-range dynamics of confinement. Understanding hadronization from first principles has proven very difficult. However, over the last two decades, progress has been made in phenomenological descriptions of hadronization, such as the Lund model. One immediate goal is to extend and test the consequences of the model in different physical domains. For instance, how well can the model describe the data at lower center-of-mass energy, where jet formation does not occur? More interestingly, how should spin degrees of freedom be incorporated in fragmentation processes? The latter is particularly important because spin admits a rich variety of fragmentation functions, posing challenges to any fragmentation model. A fundamental question is how, and to what extent, the spin of a quark is transfered to its hadronic daughters. A related goal is to understand the quantum state of the $q\bar{q}$ pair that emerges from breaking the color flux tube.

3.2.2 A Tool for Hadron Structure Studies

In the nuclear physics laboratory, hadronization has emerged over the last 5 years as a *tool* of profound importance in the analysis of hadronic structure functions: a new generation of experiments is exploiting the fact that semi-inclusive DIS measurements may, through fragmentation functions, “tag” particular flavors of struck quarks. New varieties of semi-inclusive

and exclusive processes have also introduced new *classes* of hadronization observables. For example, the measurement of the transversity distribution $\delta q(x)$ relies on the participation of the T-odd fragmentation function $H_1^{\perp}(z)$ with attendant *phase coherence* in the final state. With better understanding of the spin transfer mechanism, useful information could be gleaned about the spin structure of the produced hadron itself, such as the Λ baryon whose spin can be measured from the angular distribution of its decay products.

3.3 The Role of Quarks and Gluons in Nuclei, and Partonic Matter Under Extreme Conditions

Most of the observable matter in the universe is contained in the form of atomic nuclei. The interaction between protons and neutrons is responsible for *nuclear binding* and may be described with good success using effective theories where exchanged mesons (predominantly pions) serve as mediators. How is this binding effect manifested in the underlying quark and gluon degrees of freedom? How important is the effect of the nuclear modification of parton distributions in heavy-ion collisions? In the extreme kinematic limit where gluons carry a small fraction of the nuclear momentum and become super-dense, it becomes impossible to separate the nucleus into individual nucleons. If so, how do we probe this exotic form of partonic matter in a large nucleus?

3.3.1 Parton Distributions in Nuclei

Do quark and gluon degrees of freedom play any role in understanding the structure of nuclei? In the 1980's the European Muon Collaboration at CERN demonstrated that the quark momentum distribution of a nucleon is significantly altered when it is placed in a nuclear medium. Recent data from DIS indicate that a medium modification also occurs in the ratio of the longitudinal to transverse photo-absorption cross section at low x and Q^2. Many models have been proposed to explain the EMC effect, but no satisfactory consensus has yet been reached.

Measurements of the nuclear modification of the parton distributions provide information about the virtual particles responsible for nuclear binding. If the nucleon-nucleon interaction is mediated by the exchange of virtual mesons, it would stand to reason that such exchanges are *enhanced* in the nuclear medium. To date, however, no such enhancement has been observed. A nuclear enhancement of valence quarks, sea quarks, or gluons would be indicative of the relative importance of meson, quark, or gluon exchange at various distance scales. There are as yet no data at $x > 1$ in the scaling region, which can address the possible existence of super-dense partonic clusters in the nucleus. Also relevant are semi-exclusive experiments, observing high or low momentum backward nucleons, which can either emphasize events originating from superhigh density clusters or else pick out events involving an almost unmodified neutron target. Polarization studies of the deuteron at high energy should determine whether meson exchange or quark interchange is a dominant process when the two nucleons are very close together.

3.3.2 Relevance to High Temperature QCD

The parton distribution functions in nuclei determine the initial conditions for heavy-ion collisions, which are the only laboratory tool to search for a new state of matter: the quark-gluon plasma (QGP). The QGP is a deconfined phase of matter, which is expected to occur at very high temperatures and densities, and experiments to search for this new phase of matter are underway worldwide. Significant medium modifications of the gluon distribution are certainly expected, but their magnitude is as yet only weakly constrained by experiment. It is of great importance to the heavy-ion community that these effects be understood, as they are an essential ingredient in establishing the observation of the QGP.

3.3.3 Partonic Matter under Extreme Conditions

High energy scattering, with either electromagnetic probes or protons on nuclear targets, offers new opportunities for studying partonic matter under extreme conditions. Particularly exciting is the possibility to investigate the very-low x region where gluons are dominant. Measurements of the proton structure function $F_2^p(x)$ have shown that the gluon density rises dramatically as x decreases. Unitarity considerations indicate that the gluon densities must *saturate* at some point, perhaps through the mechanism of gluon *recombination*. This new regime of partonic matter has not yet been observed and, at the moment, it seems that we have not yet reached sufficiently low values of x. However, in heavy nuclei the effects of saturation will be revealed at much larger values of x than in ep scattering. New and proposed facilities offer for the first time the prospect of reaching the gluon-saturation regime and observing this new state of partonic matter.

4 Spectroscopy

Spectroscopy is a powerful tool in physics. For example, the color degree of freedom emerged from detailed baryon spectroscopy and flavor symmetry was first seen clearly in hadron spectroscopy. The charmonium spectrum solidified our belief in the existence of quarks and provided substantive evidence for a linearly confining quark-antiquark potential. Hadron spectroscopy will continue to be a key tool in our efforts to understand the long-wavelength degrees of freedom in Quantum Chromodynamics (QCD). This section includes an overview of experiments and theoretical calculations for the bound and resonant states of mesons and baryons. The long-range properties of QCD are central to the issues of this subfield, bringing into play its full complexity *and* a set of rich phenomena in strong interactions. The properties of QCD and the nature of confinement are among the outstanding open problems in physics. To get a coherent picture, contributions from phenomenology, QCD-based models, and lattice gauge theory (LGT) will be required. This subject is complementary to the study of structure functions and is closely linked to the hadronic models section. Hadronic spectroscopy cannot be explained using standard perturbation theory. Nonperturbative field theoretic methods will be crucial to gain understanding from the data.

Most conventional excited hadrons are regarded as excitations of the quark degrees of freedom. Theory predicts that the gluonic degrees of freedom can be excited at moderate energies. A common language used for gluonic excitation is that of the flux tube; this

plays a prominent role in many empirical models. One immediate manifestation of the possibility of coherent excited glue is the presence of *hybrid* states in the hadron spectrum. Lattice and model predictions for the mass scale of these excitations have now converged at, or just below, 2 GeV. Their quantum numbers, strong decays and production rates in electromagnetic processes have been predicted in various model and lattice studies. In particular, the existence of exotic combinations of spin, parity and charge-conjugation (J^{PC}) quantum numbers among the hybrid mesons will aid in their identification. For example, the flux tube model predicts that low lying 1^{-+} exotic hybrids have their quarks in a spin triplet. This picture is indirectly supported by lattice calculations. If correct, it implies that exotic hybrids are especially suited to production by photons.

Other new types of hadronic matter are also anticipated. These include bound states of mesons, states with a $qq\bar{q}\bar{q}$ structure, dibaryons, and $qqqq\bar{q}$ states. An example of a possible dibaryon is the H particle, whose properties are relevant to the stability of strange matter. Candidate states exist for all of these nonstandard hadrons. In a sense, these states interpolate between hadrons and nuclei and thereby provide an important empirical link between these regimes. Testing theory and models on these states will thus be a significant step in developing reliable descriptions of nuclei and nuclear matter.

Many years ago, the discovery of approximate SU(3) symmetry in the hadron mass spectrum led to a breakthrough in establishing the quark model, and is still a mainstay in particle physics curricula. As more detailed information became available, the discussion evolved into the issues of interquark forces and details of the baryon wave functions. It is now clear that nature has given us an incredible empirical gift, as is evident in the slowly varying hadron mass gaps between orbitally-excited (e.g. $^3\mathrm{P}_2$ - $^3\mathrm{S}_1$) and spin-excited (e.g. $^3\mathrm{S}_1$ - $^1\mathrm{S}_0$) mesons as the quark mass evolves from heavy to light quarks (or from above the QCD scale to below it). This surprising feature motivates the use of nonrelativistic quark models over the full range of quark masses, despite the fact that the model has no rigorous justification in light quark systems. More recently, advances in computer technology have allowed considerably improved studies of hadrons using lattice QCD techniques. One may anticipate that many of the basic aspects of QCD will be clarified through lattice studies, and these results may be abstracted by model builders for application in the regimes of high-mass excitations and scattering, which are not easily accessible to lattice studies. In the near term, we expect that progress in hadron spectroscopy will follow from a synthesis of results from lattice gauge theory, empirical quark models, and high-statistics experiments using partial wave analyses on several final states.

4.1 Mesons

The valence content of a meson is understood to be a quark and an antiquark. This is the basis for the constituent quark model (CQM) description of the mesonic structure. Even more than for baryons, this has provided a highly successful empirical description of the meson mass spectrum and various decays. This success has the added effect of providing excellent means to search for exotic hybrid mesons (mesons with quantum numbers not possible in the CQM) and glueballs (states with a substantial ‘pure glue’ component).

4.1.1 Light Mesons

Much progress has been made in this field recently, both in the scalar sector where the lightest glueball is expected and in the area of mesons with exotic quantum numbers. High quality, very high statistics data at CERN in both $\bar{p}p$ annihilation and pp central production have significantly advanced our knowledge of scalar mesons. Three states are now known with mass near 1.5 GeV, close to the low-lying scalar glueball mass predicted by lattice gauge theory. The current interpretation is that the scalar glueball and the meson nonet are strongly mixed in the three physical resonances (where only two are predicted by the CQM). It is encouraging that the two states which seem to have the largest glue content are relatively narrow. [The $f_0(1500)$ has a width of approximately 120 MeV and the $f_0(1710)$ has a width of about 160 MeV.]

There have also been reports of states with $J^{PC} = 1^{-+}$ exotic quantum numbers (which are forbidden to conventional $q\bar{q}$ quark model states) in several experiments. Experiments at BNL and VES (Serpukhov) have reported an I=1 1^{-+} exotic resonance with a mass of 1.6 GeV in three distinct decay modes. There are also recent reports of the same state in $\bar{p}p$ annihilation at rest. A second, more controversial 1^{-+} state with a mass of 1.4 GeV has been reported by two experiments, but only in $\eta\pi$ final states. Although the detailed composition these two states is still an open question, especially in view of their low mass relative to lattice and flux tube predictions for exotic hybrids, there is no question that (if confirmed) they are beyond the standard $q\bar{q}$ quark model. All of these observations have been made possible by nearly hermetic experiments with extremely high statistics combined with an excellent understanding of the detectors.

We have finally reached an era in which we see experimental evidence of gluonic excitations. In order to understand the physics of these new systems, it is important establish the spectrum in sufficient detail to see the pattern of these states. The determination of their production and decay characteristics will be important to guide future experiments and to improve our understanding of the physics of gluonic excitations. The clearest place to study decays is in a *clean* arena in which mixing is minimal. This means that initially we should determine the spectrum of states with non-$q\bar{q}$ quantum numbers. Once these are understood the analysis can be extended to non-exotic gluonic states that may mix significantly with with conventional hadrons. Certain clear opportunities for carrying out this program can be identified. For example, at present there are very little data on the photoproduction of mesons. The photon is a very interesting probe for meson production because it carries a unit of angular momentum into the reaction; using a polarized photon beam, exotics and their production mechanism can be identified unambiguously. The widely held view that hybrid states have excited gluonic flux tubes implies that they should have relatively large photocouplings.

Glueball and meson calculations on the lattice have advanced significantly in the last few years, and these results, in combination with recent high statistics data on scalar mesons, have changed our interpretation of glueball candidates considerably. The glueball spectrum in Yang-Mills theory (pure glue) is now well known; future calculations in the pure glue sector will address the physical extent and structure of glueballs. The inclusion of light-quark effects is the next challenge in lattice glueball studies, and the level of mixing between pure glueball states and nearby quarkonium states is a crucial issue. Lattice results have also

been reported for the spectrum of light exotic mesons; these show that the lightest exotic meson has $J^{PC} = 1^{-+}$ quantum numbers, and a mass near 2 GeV. Future lattice work will improve the statistical accuracy of this result and expand the study to other exotic quantum numbers. Lattice QCD will also address the much more difficult problem of meson decays, both for exotic and conventional mesons.

Hybrids are widely expected to be identifiable through their unusual strong decay amplitudes. In the flux tube model a hybrid is a state in which the flux tube is orbitally excited, and in the usual flux tube breaking picture of hadron decays this leads to a preference for "S+P" final states, such as $f_1\pi$ and $b_1\pi$, over the more familiar "S+S" modes such as $\pi\rho$, $\pi\eta$ and $\pi\eta'$. If this prediction is confirmed in exotic hybrids such as the I=1 1^{-+} π_1 states, it should be very useful in the identification of non-exotic hybrids. If this selection rule proves inaccurate, it will require dramatic revision of the present picture of exotics.

Meson form factors continue to be an important testing ground for advanced models of QCD. New experiments at JLab and Cornell are greatly advancing our knowledge of the pi meson. Similar efforts are occurring at the AGS, WASA/CELSIUS (Uppsala) and MAMI (Mainz) for the η and η' mesons.

4.1.2 Heavy quark mesons

The detailed structure of mesons containing c or b quarks has traditionally been a high energy physics subject, however future opportunities exist for nuclear physicists. The heavy quarkonium and hybrid sectors are especially attractive for the study of hadron spectroscopy, since the complications of relativistic quark motion and large decay widths, are of reduced importance. Very interesting results were found in $c\bar{c}$ mesons above open-charm threshold in the late 1970s and 1980s, such as a possible $D^*\bar{D}^*$ molecular state. In view of recent theoretical and experimental results on exotics it now appears appropriate to initiate new experiments at a high-statistics e^+e^- "tau-charm" machine. A search for charmed hybrid mesons should be a high priority. The lattice implementation of the effective theory which describes nonrelativistic QCD has predicted masses of the 1^{-+} exotic heavy-quarkonium hybrids of 4.39(1) GeV for $c\bar{c}$ and 10.99(1) GeV for $b\bar{b}$. A 1^{--} hybrid is expected to lie close in mass, and given moderate mixing between $c\bar{c}$ and hybrid $c\bar{c}$, these states should appear in e^+e^- experiments in this energy range. One may also search for the non-1^{--} states using a hadronic cascade from higher-mass $c\bar{c}$ continuum states. Model calculations predict that these states will have hadronic decay widths of less than 50 MeV.

Another key idea is to search for glueballs in J/ψ radiative and hadronic decays. Previous low-statistics experiments identified glueball candidates such as the $f_0(1710)$; with high statistics a more definitive assignment will be possible through the crucial strong branching fractions of these states. Comparison with LGT predictions of glueball couplings to meson-meson final states should allow discrimination of glueballs from other types of states, or the identification of the glue component of strongly mixed states.

A third interesting direction is the study of photon-photon collisions at high intensity e^+e^- experiments such as CLEO and BABAR. Previous results have been very useful in flagging non-CQM properties of unusual states such as the $a_0(980)$, $f_0(980)$ and $f_0(1500)$, which have anomalously small $\gamma\gamma$ widths compared to known $q\bar{q}$ states. Theoretical predictions for $\gamma\gamma$ widths have been tested for about 10 light 1S and 1P $q\bar{q}$ and $c\bar{c}$ states, but the very

limited statistics to date have precluded detailed studies of the scalar f_0 states, which would clarify the nature of glueball candidates. Finally, knowledge of the η' form factor derived from radiative decay measurements may help solve the puzzle of its mass generation.

Heavy-light meson systems (D,D^*,D_s,B,...) have been studied in detail using heavy quark effective theory (HQET), especially their weak transition amplitudes, which are described by the Isgur-Wise function. Many other interesting predictions of HQET motivate identification of the higher mass, strongly unstable heavy-light states.

CP studies at high energy machines are high priority experiments that depend on detailed understanding of various strong decays. Recently, complications in the determination of CP phases due to strong final state interaction (FSI) effects have been realized. Studies of D and D_s decays have confirmed experimentally that these FSI phases are important. A better understanding of strong interaction effects in the CP-relevant channels will be required. Similarly, determination of Cabibbo-suppressed CKM matrix elements and $D\bar{D}$ mixing parameters will require an understanding of strong interaction effects among the light hadron decay products of heavy-light mesons.

4.2 Baryons

The most basic elements of baryon spectroscopy are the ground state properties of the proton: mass, spin, magnetic moment, charge radius. The main goals of modern experiments are the full determination of the spectrum of excited states, identification of possible new symmetries in the spectrum, and illuminating the microscopic structure of states that are nominally built of three valence quarks. As mentioned above, the establishment of SU(3) symmetry was a key result in particle physics at the beginning of baryon structure studies. Advanced experimental capabilities and the ability to solve models with close approximation to QCD now allow far deeper understanding. The present status will be discussed in this subsection.

Many fundamental issues in baryon spectroscopy are still not well understood. This is largely due to the lack of data beyond the early HEP experiments of a few decades ago. The very limited knowledge of states beyond the lowest S and P wave supermultiplets provides very weak constraints on models. The possibility of new, as yet unappreciated, symmetries could be addressed with better data. For example, there may be a parity doubling in the spectrum of baryons, which would be observable in different flavor sectors. If parity doubling is a real effect, this implies that the usually anomalous axial $U(1)$ symmetry has been restored. An investigation of this possibility through a search for additional states would help clarify this issue. There is also an outstanding controversy over whether all three quarks in a baryon can be excited, or whether a quark-diquark picture is more appropriate. One can definitively distinguish between symmetric quark models and strict quark-diquark models through the discovery of a comparatively small number of new positive parity excited states, which are predicted by the symmetric qqq models but are absent from the $q(qq)$ diquark models. If these states exist, they are expected to appear strongly in certain novel final states such as $N\eta$ and $N\omega$. This issue should be resolved by a careful analysis of data obtained from a variety of initial and final states.

The other major direction is to use spectroscopic information to learn about the underlying forces that act on quarks in baryons. The mass spectrum displays the ordering of states by spin, parity, and flavor. This can be thought of as empirical splittings that provide infor-

mation about the effective degrees of freedom and has already provided the basis for many empirical models. The decay branching fractions of excited baryons to various asymptotic states and the corresponding angular distributions provide more detailed filters for models. A key tool for spectroscopy is the photocoupling amplitude, $\gamma N \rightarrow N^*$. Unlike its analog in atomic spectroscopy, this is an excitation amplitude. It can then be measured as a function of photon 4-momentum (Q^2) and provide additional structure information.

In recent years, several labs in the US (BNL, JLab) and Europe (Mainz, Bonn) have initiated vigorous programs in baryon spectroscopy. The use of modern detectors with large acceptance – effectively electronic bubble chambers – and high statistics capabilities will jump start important advances in our knowledge of baryon spectroscopy. The important new detectors are just starting to publish data, so although the picture is far from complete, the quality of the new results has been demonstrated.

The early JLab results for baryon spectroscopy involve much better statistics and kinematic coverage than all previous experiments combined. Additional reactions are being measured for the first time. Empirical analyses have determined initial results for the photocoupling amplitudes over a broad range of Q^2. Polarization of beam and target are expected to play a key role in disentangling the spectrum. At BNL, the Crystal Ball collaboration is measuring the Λ and Σ hyperon spectra at low energy, as well as N^* and Δ^* properties. The accuracy of the results is much higher than that of any previous experiment. A wealth of new data on πp and Kp reactions is being produced which will greatly improve our understanding of the light baryons, and especially of the poorly known Σ states. With a careful partial wave analysis effort (spearheaded, for example, by the recently formed Baryon Resonance Analysis Group) a detailed description of the baryon spectrum for masses below about 2.2 GeV is sought. A unified analysis of hadronic and electromagnetic reactions is required to unambiguously extract underlying physics. Hadronic beams will also be central in the experimental resolution of fundamental issues in QCD. For example, several processes are sensitive to quark mass ratios or differences. These include isospin forbidden pion production in deuteron-deuteron collisions and the decay $\eta \rightarrow 3\pi$.

Calculations are largely made with models that have quite different assumptions – constituent quark models, continuum models, and lattice gauge theories (see section 5). Each has value in elucidating features of the underlying dynamics. Lattice gauge theory solves QCD with a very small set of assumptions while constituent quark models assume the existence of massive quarks as the most significant degree of freedom. Although the empirical constituent quark models do not have a clear derivation from QCD, they nonetheless appear to incorporate much of the relevant physics of strong QCD with a small number of parameters. Given these parameters, the model predicts the spectrum of a wide range of heavy and light mesons and baryons with sufficient accuracy to make it very useful for the interpretation of experimental data on resonances. Perhaps the most significant success for baryons is the qualitatively correct description of almost all (about 50) $\gamma N \rightarrow N^*$ photocouplings.

The JLab/MIT lattice group has recently begun a program of LGT N^* calculations, with a detailed study of several of the lowest lying baryon states as a principal objective. Calculations of the masses of a few of the lowest lying states with angular momentum up to 5/2 should be completed in the near future. Work is also in progress on the photocouplings of these states. These studies will confront the emerging high quality data from the new series of baryon experiments. They will also provide information about more qualitative aspects of

baryon models, such as the appropriate fundamental degrees of freedom in the baryons, for example qqq versus $(qq)q$. Any disagreement between lattice QCD and experiment would be a striking and perhaps far-reaching discovery.

There are important roles for both constituent quark models and lattice gauge theory in describing the many phenomena seen in meson and baryon spectroscopy. At present, neither the CQM nor LGT satisfy the needs of the field for accurate, well-founded descriptions of the spectrum of low-lying and highly-excited states and their production and decay properties. First-principles lattice studies (in the quenched approximation) will soon yield much of the low-lying meson and baryon mass spectrum, but QCD-based models will be needed for guidance with respect to production and decay amplitudes.

5 The Chiral Structure of Matter, Form Factors, and Few Body Nuclei

5.1 The Chiral Structure Of Matter

The study of the chiral structure of matter is an active and fundamental field. The relevant phenomena are the properties of the Goldstone bosons as probed by their interactions and production amplitudes. These are rigorously linked to QCD by an effective (low energy) field theory, chiral perturbation theory (ChPT).

The chiral limit of QCD refers to the limit in which the bare light quark masses are zero. In this limit, QCD exhibits a 'chiral' symmetry which is not manifest in nature (and is therefore 'hidden' or 'broken'). A fundamental theorem then implies that massless (Goldstone) bosons must exist in the excitation spectrum of the theory. In the case of massless u, d, and s quarks, these are the pions, eta, and kaons. Non-zero light quark masses explicitly break the chiral symmetry of the Lagrangian with the result that the pion, eta, and kaon have finite masses. In the chiral limit, these Goldstone bosons do not interact with hadrons at very low energies, thus the small low energy interactions that are measured probe finite quark mass effects in QCD. In particular, the electromagnetic production amplitudes and the internal properties (e.g. radii, polarizabilities, decay widths will serve as fundamental tests of the chiral structure of matter. These measurements represent timely physics issues and a technical challenge for experimental physics.

The long standing prediction of Weinberg that the mass difference of the up and down quarks leads to isospin breaking in πN scattering is of special interest in this field. The accuracy of the completed experiments and of the model extractions from the deuteron pionic atom, does not yet permit a test of this fundamental prediction. An interesting possibility is the use of the pion photoproduction reaction with polarized targets to measure the isospin breaking predictions of low energy $\pi^0 N$ scattering, which is related to the isospin breaking quantity $\frac{m_d - m_u}{m_d + m_u}$ discussed in the introduction to this document.

Not all chiral predictions have been properly tested. The experimental magnitude of the πN Σ term is still uncertain. This is a fundamental quantity which gives a measure of the strange quark contribution to the nucleon mass. Important, precise experiments in low energy pion-nucleon scattering and charge exchange are presently being performed and are also in the planning stage. Another unsolved problem is a contradictory experimental

situation for the pion polarizabilities. Experiments on η and K production and scattering are in their infancy. They require both the high quality of existing beams and experiments cleverly designed to reduce the resonance contributions. Measurements of the ηN and KN interactions would provide important tests of the quasi Goldstone boson nature of these heavier pseudoscalar mesons.

Some fundamental nucleon properties (for example, electromagnetic polarizabilities) diverge in the chiral limit, indicating that they are pion dominated. Measuring these with real and virtual photons allows one to make a detailed map of their spatial distributions. The study of the non-spherical amplitudes in the nucleon and Δ wave functions also reflect significant non-spherical pion field contributions, as expected from Goldstone's theorem.

A profound example of symmetry breaking in QCD is the axial anomaly. The classical U(1) symmetry of the QCD Lagrangian is absent in the quantum theory presumably due to quantum fluctuations of the quark and gluon fields. Physical consequences are the non-zero mass of the η meson and the 2 photon decays of the pseudoscalar mesons. There is an absolute prediction of the $\pi^0 \to \gamma\gamma$ decay rate with only one parameter, N_c, the number of colors in QCD. At present the accuracy of the experiments is approximately 15%. An effort to reduce this by an order of magnitude is in progress. There are also plans being made to measure the $\eta \to \gamma\gamma$ to and $\eta' \to \gamma\gamma$ decay rates. These involve the axial anomaly and also the mixing between π^0, η, and η' mesons (which vanishes in the chiral limit). The present experimental accuracy of the η and η' two photon decay rate is approximately 15%. It appears feasible to reduce these errors by about a factor of 5. This would significantly improve the determination of the mixing matrix. Other reactions for which the axial anomaly is the dominant mechanism such as $\gamma\pi \to \pi\pi$ are also being studied.

5.2 Nucleon Electromagnetic Form Factors

The electromagnetic form factors of the nucleon have been of longstanding interest in nuclear and particle physics. Form factors describe the distribution of charge and magnetization within nucleons and allow sensitive tests of nucleon models based on Quantum Chromodynamics or lattice QCD calculations. They also are important input for calculations of processes involving the electromagnetic interaction with complex nuclei. Precise data on the nucleon electromagnetic form factors are essential for the analysis of parity violation experiments, designed to probe the strangeness content of the nucleon. The nucleon electromagnetic form factors are closely related to the newly discovered generalized parton distributions. Thus, the study of the nucleon electromagnetic form factors advances our knowledge of nucleon structure and provides a basis for the understanding of more complex strongly interacting matter in terms of quark and gluon degrees of freedom.

The proton electric (G_E^p) and magnetic (G_M^p) form factors have been studied extensively in the past from unpolarized electron-proton elastic scattering using the Rosenbluth separation technique. The maturation of polarization methods has revolutionized our ability to study electromagnetic structure. For example, the standard dipole parameterization seemed to describe the Q^2 dependence of both proton form factors well at low momentum transfer. However, new data from a polarization transfer experiment at JLab directly measures the ratio $\frac{\mu G_E^p}{G_M^p}$. Strong disagreement with the dipole form factors at moderate momentum transfer

is found, necessitating a reassessment of the longstanding picture of the reaction.

Until recently, most data on G_M^n had been deduced from elastic and quasielastic electron-deuteron scattering experiments. For inclusive measurements, this procedure requires the subtraction of a large proton contribution and suffers from large theoretical uncertainties. The sensitivity to nuclear structure can be greatly reduced by measuring the cross section ratio $d(e,e'n)/d(e,e'p)$ at quasielastic kinematics. While the precision of recent experiments at Mainz and Bonn is excellent, their results are not fully consistent. An alternative approach for precision measurements of G_M^n uses the inclusive quasielastic $^3\vec{\mathrm{He}}(\vec{e},e')$ process. By using polarization observables, these measurements are subject to different systematics than the unpolarized deuterium experiments. Experiments at various labs are in progress.

The intriguing result on $\frac{\mu G_E^p}{G_M^p}$ at high Q^2 elicited great interest in this subject. An extension to $Q^2 = 5.6$ GeV^2 is currently in progress at JLab. A precision measurement of the proton RMS charge radius is planned at Bates with BLAST to take advantage of the possibility of precision lattice QCD calculations. The planned measurement will improve the precision of r_p by a factor of three compared with the single most precise measurement from electron scattering experiments. This will be sufficient to allow high precision tests of QED from hydrogen Lamb shift measurements and to provide reliable tests of lattice QCD calculations.

Unlike the proton electromagnetic form factors, data on the neutron form factors are of inferior quality due to the lack of free neutron targets. However, recent experiments have demonstrated that G_E^n can be determined with much better precision using polarization degrees of freedom. Polarization experiments are in progress and planned at JLab on G_E^n for high Q^2, and for low Q^2 at Mainz, Bates, NIKHEF, and Bonn. This will allow the most precise search for the predicted modification of the neutron pion cloud in the nuclear medium. With future new precision data on G_E^n from Jefferson Lab, Bates and Mainz, our knowledge of the neutron charge distribution will be improved to a level comparable to that of the proton. A possible future energy upgrade of CEBAF to 12 GeV at JLab would allow extension of nucleon electromagnetic form factor measurements to much higher Q^2 values.

5.3 Few Body Nuclei

Form factors in elastic electron scattering have been essential in the investigation of nucleon and nuclear structure. At very low momentum transfer, the charge and magnetic radii of the nucleon and nuclei can be determined from the form factors. Form factors not only inform us of bulk properties such as charge and magnetic radii, but also provide the shape of the probability distributions. At low momentum transfer, the quarks in a nucleus congregate into nucleons and the traditional meson-nucleon picture of the nucleus describes the form factors well. However, at high momentum transfer on the simplest nucleus, the deuteron, it appears that the newest deuteron form factor data are consistent with the perturbative quark counting rule picture as well as the meson-nucleon picture. In order to resolve these two pictures, it is essential to extend form factor measurements of the light nuclei to the highest possible values of momentum transfer, where sensitivity to quark degrees of freedom are expected to be enhanced.

Another avenue for investigating the role of quarks in nuclei is photodisintegration of

the deuteron. In general, the momentum transfer given to the constituents in photodisintegration can be substantially larger than that in elastic electron scattering because of the large momentum mismatch between the incoming photon and the constituents of the nucleus. Thus, one might expect to see the effects of QCD in photodisintegration with beam energies of a few GeV. Indeed, it appears that recent JLab data for high energy exclusive break up of the deuteron data are consistent with the constituent counting rules while meson exchange models have failed to explain these high energy data. Recent polarization data in deuteron photodisintegration also show a very interesting and seemingly simple behavior. The induced proton polarization in deuteron photodisintegration vanishes at high energies. This is unexpected from a meson-nucleon picture of deuteron photodisintegration because of the presence of known excited states of the nucleon. These effects should be explored at high energies and at a complete set of reaction angles to determine whether we are actually seeing our first glimpse of the transition region between the nucleon-meson picture and a quark-gluon picture of a nuclear reaction.

6 Models of the Quark Structure of Matter

A wealth of experimental data is being collected in hadronic spectroscopy and deeply inelastic scattering experiments. Although these data are all correlated by the QCD Lagrangian, it is generally agreed that the dynamics of QCD make it difficult to understand the data from first principles. However, it is also believed that the majority of these data may be understood in terms of appropriate effective degrees of freedom. It is the job of models to determine these degrees of freedom, to understand their dynamics, and to employ this understanding to reliably examine new phenomena. These are necessarily scale-dependent questions; this scale dependence can be broken into three regions: structure, at scales $Q \ll 1$ GeV; substructure, at $Q \simeq 1$ GeV; and the partonic region, at scales $Q \gg 1$ GeV. An important requirement of all such models is a firm connection to the vacuum structure of QCD.

6.1 Structure

A natural language for the description of the 'structure' of hadrons is the *constituent quark* model, where constituent-quark effective degrees of freedom interact via potentials, *flux tubes*, or are confined to a bag.

The notion of the constituent quark comes from phenomenology; for this reason its definition is necessarily model dependent. Nevertheless, the success of this phenomenology indicates that some of the properties of constituent quarks, such as their effective masses and sizes, may be derivable from QCD. This is where the connection of models to experiment is the closest. Relating model predictions to data involves the calculation of observables through models of reaction dynamics, the estimation of final-state interactions and the effects of open decay channels on hadron masses and properties, and the development of tools for partial-wave analysis. This study should ultimately evolve into a description of low-energy hadron-hadron interactions and nuclear forces.

An important aspect of the analysis of hadron structure involves the study of pair creation, which has an impact on the strong decays of hadrons, and fragmentation. At present,

a microscopic basis for models of strong decays is lacking. The development of these models has been driven largely by meson strong decays, with some evidence from baryon decays. New information about the nature of these decays can be found from examining excited baryon decays and those of *exotic mesons*, and the nature of the strong production process can be accessed theoretically using lattice QCD. Exotic mesons and *hybrid baryons* should be studied in more detail on the lattice, which allows an efficient description of excited gluonic degrees of freedom and the mapping of the hadronic wave functions. There is a class of models which employs pions as effective degrees of freedom. Such models emphasize chiral symmetry and have typically been used to study N and Δ static properties. The extension of such models to describe excited states with an accuracy comparable to the constituent quark model remains an important challenge.

6.2 Substructure

The primary concern of this study is identification of the effective degrees of freedom and their interactions in terms of the fundamental fields of QCD. First principles analysis of QCD reveals several phenomena which can be used to connect to the constituents responsible for hadron structure. These include flux tubes, the constituent quarks themselves, and also topological field configurations such as *instantons*, *monopoles* and *center vortices*.

Constituent quarks appear as a consequence of dynamical chiral symmetry breaking, as visualized by models like that of Nambu and Jona-Lasinio. The instanton liquid model provides a description of the constituent quarks along with a mid-range spin-dependent interquark force as well as OZI violating amplitudes. It naturally incorporates $U(1)$ symmetry breaking, and is capable of connecting to the partonic degrees of freedom. Progress is needed to verify the importance of instanton-like configurations for low-energy quark-antiquark and diquark interactions. These issues can be addressed using methods based on analysis of the near-zero-mode eigenvalues of the Dirac operator on the lattice; which will also lead to an understanding of chiral symmetry breaking.

Flux tube like structures of the gluonic fields are believed to be responsible for confinement. Flux tubes provide a natural basis for the study of hadrons containing excited glue. The main approaches which lead to flux tubes are the strong-coupling expansion on the lattice and an effective description in terms of a dual superconductor, which may be due to condensation of monopoles or central vortices. Further studies of the internal structure of flux tubes on the lattice and in models are needed.

Given the utility of the large N_c limit of QCD as a tool for organizing the magnitudes of effects in low-energy QCD, it is important to test conclusions based on the large N_c limit on the lattice. For example, it would be useful to study the behavior of the η' mass for $N_c > 3$ on the lattice. Similarly, chiral perturbation theory should be connected to models and lattice QCD by calculations of chiral expansion coefficients. The method of QCD sum rules has proven a useful tool in revealing a connection between the QCD vacuum structure and hadron phenomenology. Finally, effective field theories (EFT) have enjoyed a resurgence of interest over the past several years. These carry the promise of providing a rigorous methodology for examining QCD in various limiting regimes (heavy quark, low energy, etc). In addition, the confrontation of theoretical calculations with experimental measurements in any of these regimes is most efficiently carried out by comparing the calculated and measured

EFT constants rather than by comparing prediction and experiment on a case by case basis.

Continuum field-theoretic models of QCD in a fixed gauge, such as light-cone or Coulomb-gauge, and Schwinger-Dyson Bethe-Salpeter models provide an important approach towards understanding hadron substructure. They address all of the relevant features of QCD such as the structure of the vacuum, chiral-symmetry breaking, confinement and strong decays, as well as hadronic interactions and the connection to the parton model. Indeed important progress has recently been made in understanding QCD and hadron physics as a problem in continuum quantum field theory. For example, while the fundamental question of the connection between QCD and the Hilbert space of observable states remains unanswered, Hamiltonian light-front methods have made promising steps toward providing a direct connection between QCD and constituent quarks. They are also making progress in calculations of the x dependence of light-front wave functions. Light-cone wavefunctions (LCWF) provide a fundamental frame-independent description of hadrons in terms of their quark and gluon degrees of freedom at the amplitude level. Furthermore, the generalized form factors measured in deeply virtual Compton scattering are given by overlaps of light-cone wavefunctions. The light-cone wavefunction representation also provides a basis for describing nuclei in terms of their meson and nucleon degrees of freedom, thus providing a rigorous basis for relativistic nuclear physics. The most challenging problem confronting light-cone theory is the calculation of hadron LCWFs from first principles in 3+1 dimensional QCD. Progress is being made with light-front Hamiltonian quantization methods such as discretized light cone quantization and the transverse lattice. Finally, the role of zero modes in understanding the condensate and chiral symmetry breaking in QCD on the light front also remains to be clarified.

Similarly, Dyson-Schwinger equation studies have made important advances, for example they provide a microscopic understanding of the dual nature of the pion as a Goldstone boson and a $q\bar{q}$ bound state. Analyses and modeling of continuum Coulomb gauge QCD can also address the dual nature of the pion and have supported the glueball spectrum obtained in lattice QCD simulations. This is one example of the potential for positive feedback between lattice simulations and continuum studies. Another is the recent lattice computation of dressed-quark and gluon propagators, which are important elements of continuum phenomenology. Since such theory and phenomenology can rapidly adapt to an evolving experimental environment they must continue to actively assist these programs. Important open questions for all continuum methods are the related issues of nonperturbative computational methods and nonperturbative renormalization. The technologies of effective field theory and lattice renormalization are greatly aiding in resolving the latter problem.

Lattice studies at this important scale should be extended to provide correlation functions of different operators. Using high accuracy data, such as vector and axial-vector amplitudes from τ decays, one can accurately calibrate lattice calculations.

6.3 Partonic region

This region of QCD structure corresponds to the parton model of deeply inelastic scattering (DIS), at large momentum transfers $Q \gg 1$ GeV. The models described above should also be explored in this regime. One important issue is to understand the connection of inclusive observables, such as structure functions, to exclusive observables such as form factors. A

related issue is to understand how partons are distributed in multiplicity. An understanding of how partons are distributed in the transverse plane is also required. These issues can be experimentally addressed by study of diffraction, multiple-parton collisions and semi-inclusive production.

An important synthesis needs to be made between the intermediate-momentum transfer (1 GeV) behavior of the parton distributions, and models of the structure and sub-structure of hadrons. One way to do this is a higher twist analysis similar to what has been done for correlators in the framework of QCD sum rules. Bloom-Gilman duality provides another important connection of this behavior to an effective description in terms of hadrons. For example at low Q and in the large N_c limit the intermediate inelastic states in a calculation of DIS in the rest frame of the proton are sharp baryon resonances, while at high Q the large number of high-mass resonances accessible forms a complete set that gives Bjorken scaling through a change to a partonic basis. These can be tested with detailed experimental information on the low-Q limit and evolution of structure functions.

A fundamental aspect of a hadron is its distribution amplitude $\phi_H(x, Q)$, which controls large momentum transfer exclusive reactions. Factorization theorems have recently been proven, which also allow one to rigorously compute types of exclusive B decays in terms of the distribution amplitudes of the final state hadrons. The fact that LCWFs are process-independent provides a profound connection between amplitudes that describe exclusive processes such as elastic form factors, two-photon reactions, and heavy hadron decays.

Other important quantities that should be better addressed by all relevant models and lattice calculations are the primordial structure functions used as input to QCD evolution. In particular an explanation for the observed sea-quark isospin and spin structure should be sought. New measurements, such as the spin-flavor antiquark asymmetry $\Delta\bar{d} - \Delta\bar{u}$, should be performed.

7 Tools

Although some of the challenging questions laid out in the previous sections are decades old, we are at a threshold for making significant progress in resolving these puzzles. This is true, to a large extent, because of the unprecedented experimental and theoretical tools which are now at our disposal. These new opportunities have been made possible by recent technological advances. For example, lattice field theory has developed into a powerful and essential tool to understand and solve QCD. A new generation of accelerators and detectors make possible experiments with unprecedented precision and kinematic range. Taking full advantage of this emerging technology will have decisive impact on hadronic physics.

7.1 Experiment

An essential foundation for progress in hadronic physics is the aggressive exploitation of present facilities and development of new ones, with a clear focus on experiments that provide genuine insight into the inner workings of QCD. In the near term, it must be a high priority to fully exploit existing modern facilities. At JLab, a 12 GeV energy upgrade will open new windows on hadronic physics. At BNL completion of the detectors will make possible full

exploitation of the unique hadron beams at RHIC. A new initiative in lattice QCD at the scale of 10 Tflops is required to exploit new advances in lattice field theory.

In addition to the present dedicated facilities supported by the Nuclear Physics program, significant opportunities exist to use lepton and hadron beams at other accelerator facilities, for example at Fermilab, the BNL-AGS, and CLEO. It is important for our field to aggressively utilize capabilities of these beams to address key issues in hadronic physics. The breadth of the effort required to give an accurate picture of the meson and exotic spectrum makes results from a variety of labs valuable.

In the longer term, a high luminosity electron ion collider would be a powerful new microscope for the examination of hadronic structure. To develop the optimal capabilities in a timely way, research and development of accelerator and detector technology will be necessary.

7.2 Theory

One of the principal reasons this is a propitious time for fundamental progress in hadronic physics is that the tools of lattice field theory and the availability of Terascale computers now make definitive calculations of hadron observables possible. Algorithms that incorporate chiral symmetry exactly on the lattice, chiral perturbation theory to extrapolate reliably from the masses at which lattice calculations are performed to the masses relevant to the physical pion mass, and Terascale computational resources provide an unprecedented opportunity for controlled solutions, which will have decisive impact on our understanding of QCD.

Similarly, advances are being made in continuum model building, effective field theory, and the theory and application of parton distributions. As a result, increased support of theory is warranted. This could include strengthening university and laboratory based research, the creation of a national postdoctoral fellowship program in hadronic physics, increased support of bridge positions, laboratory visitor programs, and the support of summer schools for undergraduate and graduate students.

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